A Measurement of the Branching ratio and Asymmetry of the Decay $\Xi^0 \to \Lambda^0\gamma$

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we have measured the Branching Ratio and Asymmetry of the Weak Radiative Ξ^0 decay into $\Lambda^0\gamma$ using KTEV data obtained during the 1999 run period. As normalization mode we used the dominant decay mode $\Xi^0 \to \Lambda^0\pi^0$. We have identified 3,056 $\Xi^0 \to \Lambda^0\gamma$ candidates with an estimated 11.4% background therein and a total of 5,770,829 $\Xi^0 \to \Lambda^0\pi^0$ decays. Acceptance and background analyses on both decay modes yields a branching ratio of $BR(\Xi^0 \to \Lambda^0\gamma)/BR(\Xi^0 \to \Lambda^0\pi^0)=(1.21\pm0.03\pm0.04)\times10^{-3}$. Analysis of the final state decay distribution yields a Λ^0 emission asymmetry parameter for this decay $\alpha(\Xi^0 \to \Lambda^0\gamma)$=-0.73±0.10.

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We report on the Fermilab KTeV experiment's analysis of the Weak Radiative Decay $\Xi^0 \to \Lambda^0\gamma$. This is an example of a Weak Radiative Hyperon Decay (WRHD) of the Ξ^0. Experimentally it is quite accessible with a branching ratio of 10^{-3}. The two most significant parameters to be measured in this decay are the branching ratio (BR), and the asymmetry α of the daughter baryon (Λ^0) emission with respect to the initial spin axis of the Ξ^0. According to Hara theorem [1] by assuming an exact SU(3) symmetry and a weak Hamiltonian completely symmetric to s and d quark exchange for the Σ^+ and Ξ^- WRHD, the decay asymmetry should be zero. In the real world, however, the quarks have distinct, non zero masses, and therefore non vanishing parity violating amplitudes are expected in the Weak Hamiltonian describing their WHRD decays [2]. By taking into account the s and d quark masses and assuming single quark transition ($s\to d\gamma$) Vasanti [3] in a 1976 paper predicted a modest, positive asymmetry for the Weak Radiative Decays depending solely on quark mass assignments. When the first measurement of the asymmetry in the Weak Radiative Hyperon decay $\Sigma^+\to p^+\gamma$ revealed a large negative value [4], a theoretical puzzle was generated. Elementary, quark level arguments appeared to be inadequate to describe the experimental results [2]. Over the years a large number of theoretical models appeared, trying to explain the Weak Radiative Hyperon Decay (WRHD) mechanism. Borasoy and Holstein in a 1999 paper [5] examined the significance of baryon resonance contributions to the Radiative Hyperon Decays. Zenczykowski [6–8] applies Vector Dominance Models (VDM) in an effort to establish a Lagrangian predicting the WRHD asymmetry values. Therefore, it is important to accurately measure the parameters of Weak Hyperon Radiative decays constraining the various theoretical models and providing guidance to the theory. In the past the KTEV Hyperon group was able to reconstruct and measure another Radiative Cascade Decay, $\Xi^0 \to \Sigma^0\gamma$ [9, 10]. Previous asymmetry and Branching Ratio measurements of the $\Xi^0 \to \Lambda^0\gamma$ radiative decay come from Fermilab experiments [11, 12], as well as from the NA48 CERN experiment [13, 14].

The KTeV experiment has been designed with the primary purpose to study CP violation effects in the neutral Kaon system as well as rare Kaon decays. It is a two beam experiment with a regenerator. The two neutral beams are generated from an 900 GeV/c proton beam directed onto a 3x3x300 mm^3 beryllium oxide (BeO) target and a system of collimators. The BeO target serves also as the origin of the KTeV coordinate system, with the Z-axis along the beam direction, X-axis towards the west of the detector and the Y-axis pointing upwards. A lead absorber and a series of dipole magnets immediately after the target eliminate photons and all charged particles. The sweeping magnets in the beamline operated in such a way that the integrated magnetic field delivered Ξ^0 hyperons with polarization ($\approx$10%) in the positive or negative vertical direction. One of the magnets was regularly reversed to allow the creation of net polarization data sample to be used for measurements of decay asymmetries. The remaining neutral particles were mainly K_L, Neutrons and Hyperons. They were allowed to decay in a 65m long vacuum tank located 94m away from the BeO target. Inside the vacuum tank, several lead scintillator detector elements with square apertures in their center, were vetoing against events with decay particles outside the sensitive area of the detector. The KTeV spectrometer follows the decay vacuum tank and consists of 4 drift chambers two on each side of a magnet. It provided charged particle momentum resolution of $\sigma(P)/P=0.38\%\oplus P\times 0.016\%$ where P is expressed in units of GeV/c. Detectors at the edges of the drift chambers were vetoing against particles directing themselves outside the acceptance region of the experiment. Downstream of the spectrometer after the last drift chamber there is a set of 9 Transition Radiation Detectors, followed by a plane of vertically oriented trigger hodoscopes and an electromagnetic calorimeter. All three detectors have two beam holes. The electromagnetic calorimeter consists of 3100 crystals of pure CsI, 50cm (27 radiation lengths) in depth. For energies measured in GeV the detector provides resolution of $\sigma(E)/E\approx 0.4\%\oplus 2\%/\sqrt{E}$ with a position resolution of approximately 1mm. A lead wall with 10 cm thickness follows the CsI calorimeter and immediately after it there is the Hadron-Anti (HA), a hodoscope array with a single hole accommodating both beams. The Hadron-Anti provides a veto for hadronic showers. The muon veto system, which follows the Hadron-Anti, consists of three steel walls and two hodoscope arrays. In the beam hole of the first steel wall there are two scintillation counters providing a trigger for highly energetic, forward going, charged particles. The decay products of the $\Xi^0 \to \Lambda^0\gamma$ are an energetic proton directed in one of the beam holes, a π^- and a photon hitting the calorimeter, while the decay products of the normalization mode $\Xi^0 \to \Lambda^0\pi^0$ are an energetic proton going through one of the beam holes, a π^- and two photons hitting the calorimeter. The trigger of the KTeV experiment is built on a three level architecture. The first level Hyperon trigger, designed to run at 53MHz, combines raw signals from various veto detector elements, the total energy deposited in the CsI calorimeter, and the trigger hodoscopes. The second level Hyperon trigger processes, include a fast counter of individual clusters in the calorimeter requiring at least two clusters, a fast track finder algorithm requiring a track pointing into one of the beam holes and a drift chamber hit counting algorithm requiring at least two hits in the Y-view at each of the two drift chambers. The hardware related dead time for level two operations is $\approx 2\mu$secs with an additional $\approx 10\mu$secs required for the event to be moved in a centralized data buffer. The third level trigger performs a full event reconstruction for events pulled from the buffer. For the hyperon triggers the requirements (implemented by software) were at least two X and Y track candidates, one vertex candidate with the momentum of the positive track at least 2.5 times the momentum of the negative one, one track matching a cluster in the calorimeter and another matching a beam hole, an X track candidate with momentum higher than a minimum value and vertex quality cuts for possible Ξ^0 candidates. In this analysis we have used two hyperon triggers. They are composed of the level 1, 2 and 3 trigger elements we described above and their only two differences are the inclusion of the Hadron-Anti and the prescale factor. Hyperon trigger 11 had a prescale factor 1/7 allowing one out of 7 events to be written on tape. Hyperon trigger 10 had a prescale factor 1/1. Trigger 10 vetoed on a signal of more than 2.5 MIP's in the Hadron-Anti hodoscope rejecting almost 60happens because the final state π^- of both signal and normalization mode often showers in the CsI calorimeter or lead. Separate analysis of trigger 10 data revealed that the signal and normalization mode were similarly affected by this requirement resulting in no associated systematic error. There was no Hadron-Anti requirement at trigger 11. We established a set of cuts to accept the signal and the normalization mode. The cuts applied for the normalization mode were the following:
Number of neutral clusters at the CsI calorimeter greater than one. Exactly two charged tracks where the highest momentum track must be positively charged and considered to be a proton, while the lowest momentum track must be negatively charged and considered a π^-. The proton momentum had to be between 85 and 600 GeV/c while the π^- momentum between 5 and 150 GeV/c. The CsI cluster associated with the π^- track must have energy less than 90% of the π^- momentum. The X and Y coordinates of the π^- track projected on the CsI calorimeter must satisfy the following fiducial cuts:
$0.235\text{m} < |X_{\pi^-}|$ or $|X_{\pi^-}| < 0.065\text{m}$ or $|Y_{\pi^-}| > 0.085\text{m}$
These requirements ensure that the π^- cluster is fully contained in the CsI active volume. For the proton we

required $0.08\mathrm{m} < |X_P| < 0.22\mathrm{m}$ and $|Y_P| < 0.07\mathrm{m}$ to ensure that its trajectory is directed in one of the beam holes. The invariant mass of the pπ^- pair should lie within 10 MeV of the Λ^0 mass. Assuming that the proton and π^- are products of a Λ^0 decay and that the Z coordinate of the Λ^0 decay vertex lies at the point of closest approach of the p and π^- trajectories, we applied the following fiducial cuts at the Λ^0 vertex:
The Z coordinate of the vertex must be greater than 95 m and less than 158 m. The absolute value of the Y/Z ratio must be greater than 0.00043 and the absolute value of the X/Z ratio between 0.000376 and 0.00124. We required the highest energy neutral cluster on the CsI to be greater than 5GeV, the second highest energy cluster greater than 1GeV and the sum of their energies to be greater than 18GeV. The two neutral and the π^- clusters had to be at least 20cm apart from each other on the CsI calorimeter. In order to eliminate the background from Kaon decays into $\pi^+\pi^-\pi^0$ we calculated the invariant mass of the event assuming that it is a Kaon decay into two charged and one neutral pion (decaying immediately into two photons) with decay vertex at the point of the two charged tracks closest approach. We then required that the calculated invariant mass be larger than 0.55GeV. Finally we calculated the Ξ^0 decay vertex by using the center of momentum method. The direction of Ξ^0 is given by two points, the origin of the KTeV coordinate frame (which coincides with the target position) and the point (x_{cm},y_{cm},z_{CsI}), where z_{CsI} is the position of the calorimeter shower maximum. The x_{cm} and y_{cm} coordinates are given by:
$x_{cm} = \frac{P_\Lambda \cdot x_\Lambda + k_1 \cdot x_1 + k_2 \cdot x_2}{P_\Lambda + k_1 + k_2}$ and $y_{cm} = \frac{P_\Lambda \cdot y_\Lambda + k_1 \cdot y_1 + k_2 \cdot y_2}{P_\Lambda + k_1 + k_2}$
Here P_Λ is the reconstructed Λ^0 momentum, x_Λ and y_Λ are the coordinates of its trajectory projected at the plane z-z_{CsI}, and k_1, k_2 the two highest energy neutral clusters assumed to be photons from a π^0 decay. After the reconstruction of the Ξ^0 direction we define the X_{Ξ^0} and Y_Ξ coordinates of its decay vertex as the x and y coordinates of the intersection points of the Ξ^0 and Λ^0 trajectories projected on the x-z and y-z planes. The Z_{Ξ^0} coordinate of the Ξ^0 decay vertex was taken to be the average value of the two z values calculated in the x-z and y-z planes. We applied at the Ξ^0 vertex the same fiducial cuts we applied at the Λ^0 with the extra requirement that the Λ^0 decay vertex must be after the Ξ^0 one. A total of 5,770,829 events satisfied our criteria, with an acceptance of 0.04824±0.00011. The acceptance was estimated from 3,999,908 generated $\Xi^0 \to \Lambda^0\pi^0$ decays. The corresponding flux of the normalization mode was 119,627,467±277,290.
The selection cuts for the signal were the following:
Exactly two charged tracks and one or two neutral clusters on the calorimeter. We assigned the proton and π^- and we applied the same momentum and containment cuts exactly as we did in the normalization mode selection process. We also required that the π^- deposited energy in the CsI is less than 90% its momentum and we applied the same Λ^0 vertex containment cuts. We required the reconstructed proton π^- invariant mass to be within 5.MeV of the Λ^0 mass, in an effort to to reduce the background. The Ξ^0 vertex was calculated by using again the center of momentum method, taking into account only the Λ^0 and the highest energy photon. The same fiducial cuts for that vertex were applied as in the normalization mode case, along with the requirement that the Λ^0 vertex must occur after the Ξ^0 one.
In order to reduce the background and the number of events processed, we required the following additional cuts:
The $\Lambda^0\gamma$ invariant mass to be within 40.MeV of the Ξ^0 one and the P_T balance at the Ξ^0 vertex less than 70MeV. $|\Delta Z_{\Xi^0}| \leq$15.m, where ΔZ_{Ξ^0} is the difference of the calculated Ξ^0 vertex Z_{Ξ^0} coordinate, from the two z values calculated in the x-z and y-z planes. Primary Λ^0's were eliminated by the requirement of a transverse momentum balance greater than 30.MeV at the Λ^0 vertex, assuming that the event is a primary Λ^0 emanating from the BeO target with an accidental neutral cluster on the CsI. In an effort to increase the accepted number of signal events, we allowed events with two neutral clusters, assuming that the cluster with the lowest energy is an accidental hit on the calorimeter. For those events, in order to eliminate the $\Lambda^0\pi^0$ Cascade and the $\pi^+\pi^-\pi^0$ Kaon decays we imposed three additional requirements:
First, the calculated Kaon mass (as described in the normalization selection criteria) should be greater than 0.55GeV. Second and third, assuming that it is a $\Lambda^0\pi^0$ cascade decay, the calculated π^0 mass less than 0.1GeV and the distance between the Cascade and π^0 decay vertices on the Z axis greater than 10m. Another background source we encountered was from Kaon decays into $\pi^+\pi^-\gamma$. This type of background was eliminated by assuming that the observed candidate is a Kaon $\pi^+\pi^-\gamma$ decay at the Λ^0 vertex. Then we required that the calculated Kaon mass must be greater than 0.5GeV. For this cut, only the highest energy neutral cluster was used. From Monte Carlo studies we required that the expression
$F = \frac{(y_k - y_\Lambda)\cdot P_x^\Lambda - (x_k - x_\Lambda)\cdot P_y^\Lambda}{P_z^\Lambda} + \frac{x_k \cdot y_\Lambda - x_\Lambda \cdot y_k}{Z_{CSI}}$
must be less that 0.025mm for the highest energy photon cluster and greater than 0.05mm for the second neutral cluster (if any). Here $P^\Lambda_{x,y,z}$ are the x,y and z components of Λ^0 momentum x_Λ, y_Λ, x_k, y_k the x and y coordinates of the Λ^0 and the photon cluster at the CsI shower maximum plane and Z_{CSI} is the Z coordinate of the calorimeter shower maximum plane. The expression F=0 was derived from a detailed analysis of the two body $\Xi^0 \to \Lambda^0\gamma$ decay requirement that the P_T balance at the decay vertex is zero. The remaining background was from Ξ^0 decays into $\Lambda^0\pi^0$ where a soft photon is lost in the beam holes, almost collinear with the Ξ^0. The final and

most effective cut in reducing that type of background was the requirement that $\chi^2 \leq 2.65$, where the quantity χ^2 was defined as:
$\chi^2 = (\frac{k_{miss}}{3.55})^2 + (\frac{\Delta z_{\Xi}}{3.07})^2 + (\frac{k-41.94}{18.48})^2$
Here k is the photon energy, ΔZ_{Ξ} is the difference of the cascade vertex Z_{Ξ^0} coordinate, from the two Z values calculated in the x-z and y-z planes and k_{miss} is the calculated missing photon energy if we assume that the event is a $\Lambda^0\pi^0$ decay with a photon along the Cascade direction missing detection in the beam hole. The numbers appearing in the χ^2 expression were estimated from Monte Carlo studies and the 2.65 upper limit was taken so in order to keep the residual background not much higher than 10%. A total of 3,056 events satisfied our criteria with a background of 351±25 therein. The background comes from $\Lambda^0\pi^0$ (316) and $\Sigma^0\gamma$ (35) cascade decays with a soft photon escaping detection. It was estimated from 59,080,201 $\Lambda^0\pi^0$ and 499,903 $\Sigma^0\gamma$ generated cascade decays. The Branching Ratio for the $\Xi^0 \to \Sigma^0\pi^0$ decay was taken to be $(3.34\pm0.05)\times10^{-3}$.[9]The $\Lambda^0\gamma$ acceptance was estimated from 999,907 generated events to be 0.01874±0.00014. The resulting signal flux was found to be 144,344±3,379 $\Xi^0 \to \Lambda^0\gamma$ decays.The resulting branching ratio is:
$BR(\Xi^0 \to \Lambda^0\gamma)/BR(\Xi^0 \to \Lambda^0\pi^0)=(1.21\pm0.03)\times10^{-3}$
where the error shown arises from the statistical error of the signal, normalization modes and background as well as from the errors of the signal and normalization acceptances. We examined various possible sources of systematic uncertainty on the Branching Ratio measurement. The systematic uncertainty on the acceptance is induced by uncertainty on the asymmetry in the Monte Carlo generator. The estimation of the $\Xi^0 \to \Lambda^0\gamma$ acceptance was based on a Monte Carlo data sample that was generated with a decay asymmetry value of -0.70. After inserting various asymmetry values in the generator, in the range from 0.0 to -1.0, and reanalyzing the data we assigned a $\pm0.02\times10^{-3}$ systematic error to the branching ratio. Another possible source of uncertainty in the signal and normalization mode acceptances, was the effect of hadronic showering by π^- on the Hadron-Anti veto. Since the Hadron-Anti was not included in the simulation package we used, we devised a simple analysis method to examine if it affected the signal and normalization modes similarly, canceling thus out in the Branching Ratio measurement process. We took advantage of the fact that the Hadron-Anti requirement was only present in the trigger 10 and that trigger 11 requirements were the same as trigger 10 except the 1/7 prescale factor and Hadron-Anti. By using trigger 11 data with the trigger 10 on and trigger 10 off we derived correction factors depending on the π^- momentum and position on the CsI calorimeter, accounting for the Hadron-Anti. This way we were able to account for the Hadron-Anti in the data sample selected by trigger 10. We proved that the signal and normalization mode events were effected the same

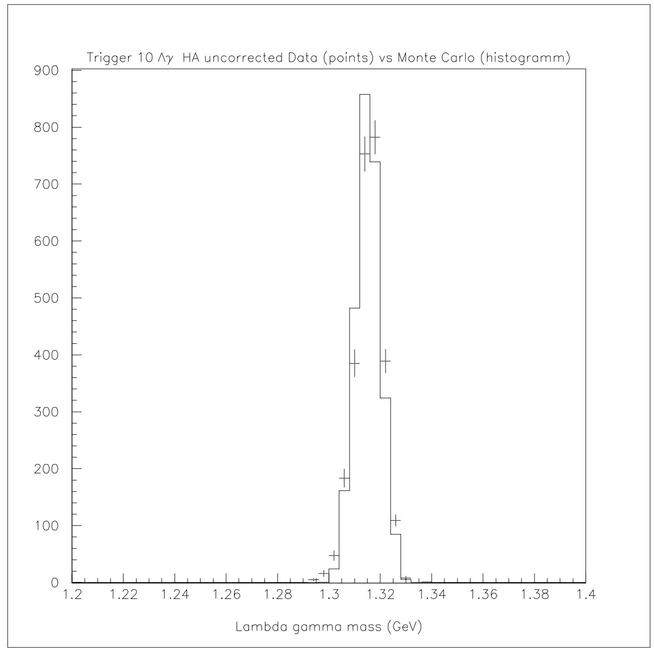

FIG. 1: The plot of $\Lambda^0\gamma$ invariant mass calculated from trigger 10 data. The points correspond to data and the Histogram to Monte Carlo values. The data points are corrected for background bin by bin.

way by the Hadron-Anti requirement and no systematic error was assigned. However, from differences in Branching Ratio measurements obtained from separate analysis of trigger 10 and trigger 11 data we assigned an extra $\pm0.02\times10^{-3}$ systematic error due to possible trigger differences not accounted in the Monte Carlo.
The background uncertainty and its possible effect on the branching ratio was estimated by varying the χ^2 (last) cut. The branching ratio results were found statistically consistent for χ^2 cut values between 1 and 3. We did not assign any systematic error to the Branching Ratio caused by background uncertainty.
We finally explored the sensitivity of our branching ratio result to the other analysis cuts, by varying a number of them. We found the branching ratio results statistically consistent except for the Ξ^0 vertex Z range requirement between 95. and 138.m. We varied the Cascade vertex Z coordinate fiducial cuts the same way for both, the signal and normalization modes. After reanalyzing the data we assigned a systematic error $\pm0.02\times10^{-3}$ to the branching ratio due to uncertainty in the reconstruction of the Ξ^0 vertex. The total systematic error assigned to the branching ratio was $\pm0.04\times10^{-3}$ and this gives our final result:
$BR(\Xi^0 \to \Lambda^0\gamma)/BR(\Xi^0 \to \Lambda^0\pi^0) = (1.21\pm0.03\pm0.04)\times 10^{-3}$
We also obtained from the data the value of the asymmetry parameter $\alpha(\Xi^0 \to \Lambda^0\gamma)$. This parameter is directly determined from the up-down asymmetry in the

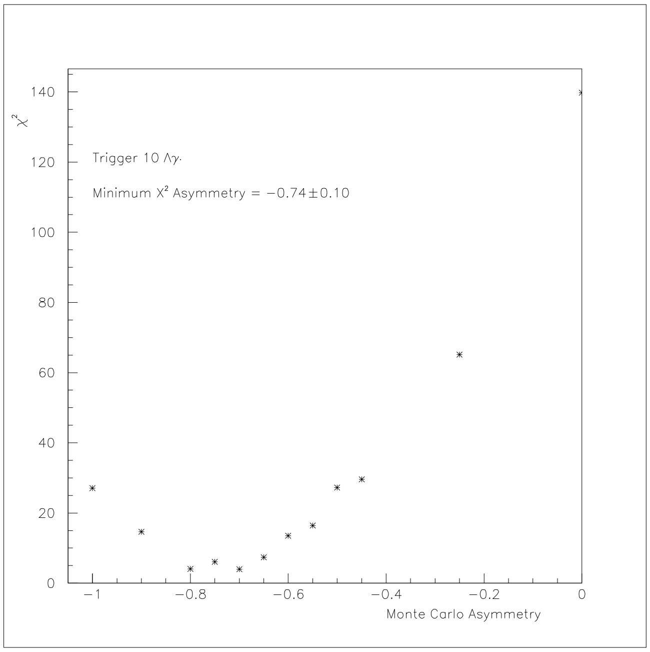

FIG. 2: The plot of χ^2 comparison of background subtracted trigger 10 data cosθ distributions to the Monte Carlo. A second degree polynomial fit yielded the minimum value at α=-0.74.

decay distribution of polarized Ξ^0's. However since the degree of Ξ^0 polarization in our data is $\approx$10% the power of this approach is limited. For an unpolarized Ξ^0 decaying into a $\Lambda^0\gamma$, angular momentum conservation requirements dictate that the longitudinal polarization of the Λ^0 should be -$\alpha(\Xi^0 \rightarrow \Lambda^0\gamma)$. Therefore the subsequent weak decay $\Lambda^0 \rightarrow p\pi^-$ asymmetry ($\alpha(\Lambda^0 \rightarrow p\pi^-)$=0.642 [16]) can be used as an analyzer of the polarization. In our analysis, in order to get the asymmetry we generated various sets of Monte Carlo $\Xi^0 \rightarrow \Lambda^0\gamma$ decays each with a different asymmetry value from a range between 0.0 and -1.0.From those sets we constructed unpolarized simulated cascade decays by taking into account the KTeV magnetic field orientation. Similarly, we constructed unpolarized Ξ^0 decays from the real data. After normalizing the number of simulated to the number of real data, we compared the cos(θ) distributions and a χ^2 value representing the data agreement with the Monte Carlo was extracted for every value of the asymmetry inserted in the Monte Carlo generator. Here θ is the angle between the proton and the Ξ^0 in the Λ^0 frame of reference.We used 10 bin histograms with cos(θ) values from -1 to 1. The cosθ distribution we derived from data was background corrected bin by bin, in accordance with values we estimated from Monte Carlo studies. The asymmetry of the decay was the one that gives the best agreement with the data, that is, the lowest value of χ^2. It was extracted after fitting a parabola to the values of χ^2 as a function of asymmetry and it was found to be $\alpha(\Xi^0 \rightarrow \Lambda^0\gamma)$=-0.73$\pm$0.10. The error assigned to the asymmetry comes from two sources. Background uncertainty and accuracy of the α measurement process. Background uncertainty effects were assessed by redoing the analysis without any background subtraction, separately for trigger 10 and 11 data. We found lower asymmetries by values between 0.07 and 0.09 respectively. We assigned a systematic error of $\pm$0.08 due to background uncertainty. The error related to the accuracy of the fitting process was determined by calculating the change ($\Delta\alpha$) of the asymmetry which changes (on the fitted parabola) the minimum χ^2 by a predefined value. The value was taken to be the maximum distance of the data points from the fitted parabola. $\Delta\alpha$ was found to be $\pm$0.05 and it was a measure of the "flatness" of our parabola. A total error of $\pm$0.10 was assigned to the asymmetry value.

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